Exclusive Measurement of the $pp \to nn\pi^+\pi^+$ Reaction at 1.1 GeV

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First exclusive data for the $pp \to nn\pi^+\pi^+$ reaction have been obtained at CELSIUS with the WASA detector setup at a beam energy of $T_p = 1.1$ GeV. Total and differential cross sections disagree with theoretical calculations, which predict the $\Delta\Delta$ excitation to be the dominant process at this beam energy. Instead the data require the excitation of a higher-lying Δ state, most likely the $\Delta(1600)$, to be the leading process.

Two-pion production in nucleon-nucleon collisions connects $\pi\pi$ dynamics with baryon and baryon-baryon degrees of freedom. Among the various reaction channels the $pp \to nn\pi^+\pi^+$ reaction is special, since the direct excitation of N^* resonances and their subsequent decay into the $\pi^+\pi^+$ channel is excluded by isospin. Hence it was expected that in the energy region considered here only the $\Delta\Delta$ process would play the dominant role. Indeed, the detailed calculations from the Valencia group [1] predict the $\Delta\Delta$ excitation to be the leading process at energies $T_p > 1$ GeV. However, in a recent isospin decomposition of the total cross sections for the various $NN\pi\pi$ exit channels we have shown [2] that this assumption is inconsistent with the experimental total cross sections.

Due to the particular selectivity of the $pp \to nn\pi^+\pi^+$ reaction only $I = 3/2$ single resonance excitations can contribute. Therefore we proposed [2] that the excitation of a higher-lying Δ state, presumably the $\Delta(1600)$ might be the leading process in this channel, since due to kinematics the $\Delta(1232)$ state cannot decay by emission of two pions.

A more recent theoretical study [3] of two-pion production in NN collisions includes many additional processes, such as *e.g.* nucleon pole terms. That way good agreement is obtained with the total cross section data for the $pp \to nn\pi^+\pi^+$ channel, however, at the same time the $pp \to pp\pi^0\pi^0$ cross section is massively overestimated for $T_p > 1$ GeV.

In order to shed more light into this conflicting situation and since there exist no differential cross sections at all for this channel we have undertaken exclusive measurements of the $pp \to nn\pi^+\pi^+$ reaction at $T_p = 1.1$ GeV using the WASA detector [4] with the hydrogen pellet target system at the CELSIUS storage ring of the Theodor Svedberg Laboratory in Uppsala. The detector has nearly full angular coverage for the detection of charged and uncharged particles.

The forward detector part consists of a thin-walled window plastic scintillator hodoscope (FWC) at the exit of the scattering chamber, followed by straw tracker, plastic scintillator quirl (FTH), forward range hodoscope (FRH) consisting of 24 cake-like segments and, finally, the forward interleaving (FRI) and veto hodoscopes.

The central detector comprises in its inner part a thin-walled superconducting magnet containing a minidrift chamber for tracking and in its outer part a plastic scintillator barrel surrounded by an electromagnetic calorimeter consisting of 1012 CsI (Na) crystals. The positively charged pions were detected and identified in the central detector.

Neutrons were detected in the forward detector. They were identified by the requirement of having no signal in the thin-walled window hodoscope, straw tracker and quirl, however a signal due to recoil protons in the range hodoscope. If the recoil protons were produced within the first three layers of the FRH, then these recoil protons could also be detected in the succeeding Forward Range Interleaving (FRI) hodoscope [5], which provides a more detailed angular information for the primary neutrons.

The trigger was set to two charged particles in the central detector and two neutron candidates in the forward detector. A neutron candidate was identified by having an energy deposit (by recoil protons) of larger than 40 MeV in a segment of the FRH with simultaneously zero hits in the preceding thin-walled detectors FWC, straw tracker and FTH.

The efficiency of the neutron detection was determined by means of the $pp \to pn\pi^+$ reaction, which was identified by detecting p and π^+ in the central detector yielding a kinematically complete measurement. From the knowledge of the four-vectors for p and π^+ the direction of the emitted neutron could be reconstructed. Comparison of the expected hits in the forward detector with actually identified neutron events provides the desired information on the efficiency.

The efficiency and acceptance correction of the full data has been performed with help of Monte Carlo simulations of the detector setup and performance. The absolute normalization of the data was achieved by normalizing to elastic scattering data — measured simultaneously with the $pp \to nn\pi^+\pi^+$ data.

With the four-vectors of the two pions and the angular directions of the two neutrons we have measured the $pp \to nn\pi^+\pi^+$ events with two kinematic overconstraints. Thus the data were subjected to a corresponding kinematic fit.

The energy dependence of the total cross section is displayed in Fig. 1. The total cross section value from this work has been published already in Ref. [2] in connection with the isospin decomposition of two-pion production data. It is in good agreement with previous bubble-chamber data from KEK [6], however, a factor of five larger than predicted by the Valencia calculations [1]. This huge discrepancy was the primary reason to introduce the excitation of a higher-lying Δ as a possible explanation in Ref. [2].

The total cross section of the $pp \to pp\pi^0\pi^0$ reaction keeps rising from threshold up to $T_p \approx 1$ GeV, where it levels off until 1.2 GeV. Thereafter it continues steeply rising until 1.5 GeV, where it finally levels off again - see Figs. 1 and 3 in Ref. [2]. As has been demonstrated there, the low-energy structure is due to the Roper resonance [9], whereas the renewed rise at higher energies can be associated with the dominance of the $\Delta\Delta$ excitation [10]. Since the latter describes both total and differential cross sections for this channel quite well for $T_p > 1$ GeV, a possibly faulty description of the $\Delta\Delta$ process can be excluded as reason for the failure of the theoretical prediction in the $nn\pi^+\pi^+$ channel.

Figs. 2 - 4 show a selection of eight differential

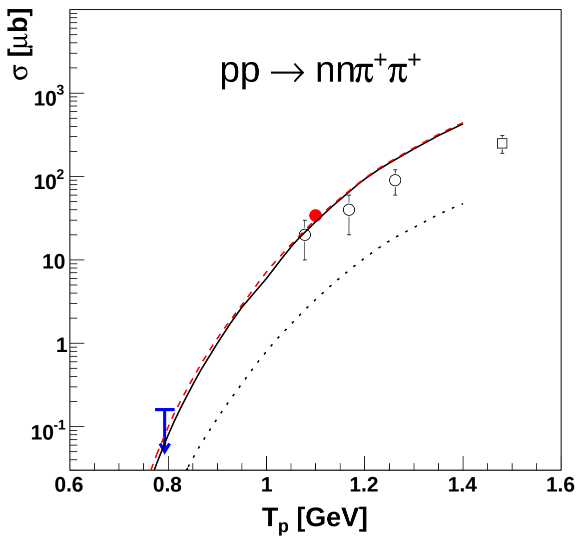

Figure 1. Energy dependence of the total cross section for the $pp \to nn\pi^+\pi^+$ reaction. Open symbols denote previous bubble chamber measurements [6,7]. The arrow gives the upper limit obtained at COSY-TOF [8] and the filled circle represents the experimental result of this work. The dotted line shows $\Delta\Delta$ calculations as used for the description of the $pp \to pp\pi^0\pi^0$ reaction [10]. The dashed line represents calculations of the $\Delta(1600) \to \Delta\pi$ process and the solid line gives the coherent sum of both processes.

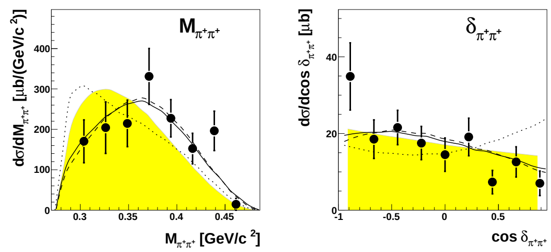

Figure 2. Distribution of the $\pi^+\pi^+$ invariant mass $M_{\pi^+\pi^+}$ (**left**) and the $\pi^+\pi^+$ opening angle $\delta_{\pi^+\pi^+}$ (**right**) for the $pp \to nn\pi^+\pi^+$ reaction at $T_p = 1.1$ GeV. Solid dots represent the experimental results of this work. The shaded areas denote phase space distributions. The dotted lines show $\Delta\Delta$ calculations as used for the description of the $pp \to pp\pi^0\pi^0$ reaction [10]. The dashed lines are calculations of the $\Delta(1600) \to \Delta\pi$ process and the solid lines give the coherent sum of both processes. All calculations are normalized in area to the data.

cross sections: the differential distributions for the invariant masses $M_{\pi^+\pi^+}$, M_{nn}, $M_{n\pi^+}$, $M_{nn\pi^+}$ and $M_{n\pi^+\pi^+}$, the opening angle between the two pions $\delta_{\pi^0\pi^0}$, the π^+ angle $\Theta_{\pi^0}^{c.m.}$ as well as the angle $\Theta_{nn}^{c.m.}$ of the nn system – all in the center-of-mass system (cms). Note that for a four-body reaction with unpolarized beam and target there are seven independent single differential distributions. The $\delta_{\pi^+\pi^+}$ distribution in fact is correlated with the $M_{\pi^+\pi^+}$ spectrum as discussed in some detail in Refs. [11,12].

In the figures the data are compared to pure phase space distributions (shaded areas in Figs. 2 - 4) as well as to calculations (dotted, dashed and solid lines in Figs. 1 - 4), which will be discussed in the following. As a convention we show in Figs. 2 - 4 all theoretical distributions normalized to the experimental cross section. This is because we are interested here in the shape of the differential distributions. For the comparison with the absolute cross section see Fig. 1.

Though the statistics of the data is limited we see that part of the experimental differential distributions deviate significantly from phase space, in particular the invariant mass distributions. We observe the $M_{\pi^+\pi^+}$ spectrum to be broader in its distribution compared to phase space, whereas the experimental M_{nn} spectrum, which is kind of complementary to the $M_{\pi^+\pi^+}$ spectrum, is substantially narrower than phase space. This behavior signals the excitation of a system which requires a large internal energy: in order to reach a maximum possible excitation energy of this system, the two involved neutrons must have minimal relative kinetic energy.

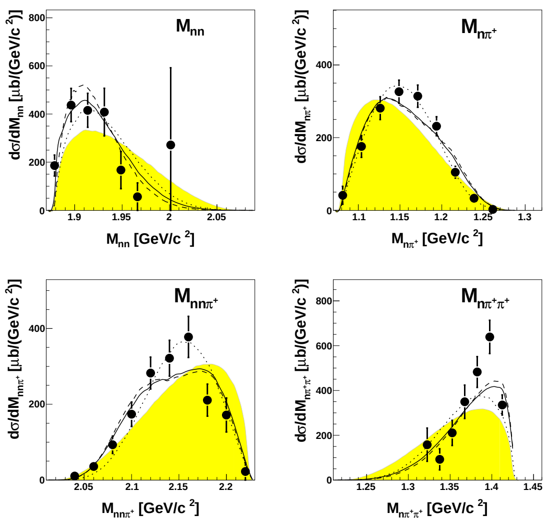

Figure 3. Same as Fig. 2 but for the distributions of the invariant masses M_{nn} (**left top**), $M_{n\pi^+}$(**right top**), $M_{nn\pi^+}$ (**left bottom**) and $M_{n\pi^+\pi^+}$(**right bottom**).

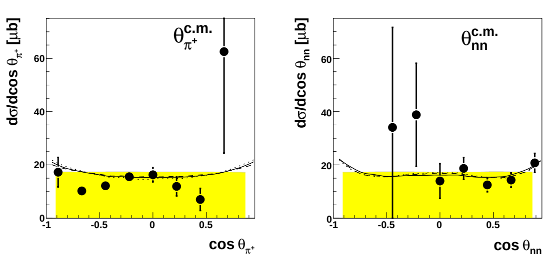

Figure 4. Same as Fig. 2 but for the distributions of the π^+ angle $\Theta_{\pi^+}^{c.m.}$ (**left**) and of the angle $\Theta_{nn}^{c.m.}$ of the nn system (**right**), both in the center-of-mass system.

Next we confront the data with theoretical predictions [1] of the Valencia group and subsequent modifications of the original calculations. In Ref. [1] three processes have been considered to feed the $pp \to nn\pi^+\pi^+$ reaction:

- the $\Delta\Delta$ process, which is considered to be the leading process for $T_p > 1$ GeV,
- the contribution from nonresonant chiral terms according to graphs (1) - (3) in Ref. [1], which shows a phase space like behavior and is expected to be the leading contribution for $T_p < 1$ GeV and finally
- the contribution from the excitation of the Roper resonance with subsequent single-pion decay and associated nonresonant emission of a second pion, graphs (6) - (7) in Ref. [1]. This contribution is the smallest one in the calculations of Ref. [1]. Accounting for the finding in Ref. [9] that the Roper contribution is largely overestimated for $T_p > 1$ GeV in Ref. [1], this contribution should be insignificant for the data discussed here. We note in passing that in principle also a double Roper excitation, i.e. excitation of the Roper resonance in each of the participating nucleons could feed the $pp \to nn\pi^+\pi^+$ reaction, however, such a process must be even much rarer than the single Roper process discussed here.

In Ref. [10] we have demonstrated that the differential data for the $pp \to pp\pi^0\pi^0$ channel in the region of the $\Delta\Delta$ excitation are not well described by Ref. [1], which assumes ρ exchange to be dominating for this process. However, with π exchange as the leading process good agreement with the data is found. This is in accordance with the finding of Ref. [3] that ρ exchange is of minor importance.

The dotted lines in Figs. 2 - 4 show the predictions for the $\Delta\Delta$ process calculated according to Ref. [10], which though renormalized in area give large deviations from the measured distributions - in particular in the $M_{\pi^+\pi^+}$ and $\delta_{\pi^+\pi^+}$ spectra. For the $M_{\pi^+\pi^+}$ spectrum these calculations predict a low-mass enhancement, which is absent in the data. With regard to the $\pi^+\pi^+$ opening angle $\delta_{\pi^+\pi^+}$ these calculations predict preferential parallel and antiparallel emissions of the two pions, which again is not supported by the data.

Next we calculate the excitation of the $\Delta(1600)$ and their subsequent decay $\Delta(1600)^{++} \rightarrow \Delta^+\pi^+ \rightarrow n\pi^+\pi^+$ by modifying graph (9) of Ref. [1] accordingly. This calculation is shown by the dashed lines. They differ from the $\Delta\Delta$ results in particular in the $M_{\pi^+\pi^+}$ and $\delta_{\pi^+\pi^+}$ spectra reaching there good agreement with the data. Finally we superimpose the $\Delta(1600)$ and $\Delta\Delta$ processes destructively as required by the isospin decomposition results [2]. This is shown by the solid lines, which actually are very close to the dashed ones, since the $\Delta(1600)$ process is the dominating process. The strength of this process has been adjusted to fit the total cross section data.

Note that since both processes are connected with a double p-wave emission of the pion pair, the angular distributions for pions and neutrons are very similar. Hence these angular distributions cannot discriminate between both processes.

Summarizing we have presented first exclusive measurements of the $pp \rightarrow nn\pi^+\pi^+$ reaction. The data show evidence for excitation and decay of a higher-lying Δ resonance, possibly the $\Delta(1600)$. The description of the differential data is consistent with that of the total cross section and with the description of the data in other channels as required by the isospin decomposition.

We acknowledge valuable discussions with L. Alvarez-Ruso, C. Hanhart, E. Oset and C. Wilkin on this issue. We are particularly indebted to L. Alvarez-Ruso for using his code. This work has been supported by BMBF (06TU9193), Forschungszentrum Jülich (COSY-FFE) and DFG (Europ. Graduiertenkolleg 683).

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